Study of parameters influencing the compressive strength of Compressed Earth Blocks

To cite this article: Lavie Arsène Mango-Itulamya and Nathalie Fagel 2022 *J. Phys.: Conf. Ser.* **2368** 012004

Study of parameters influencing the compressive strength of Compressed Earth Blocks

Lavie Arsène Mango-Itulamya[1,*] and Nathalie Fagel[1]

[1] Argiles, Géochimie et Environnement sédimentaires, Département de Géologie, Quartier Agora, University of Liège, 4000 Liège, Belgium

Email: mangoarsene@gmail.com

Abstract. This work aims to study four parameters that influence the compressive strength of compressed earth blocks (CEB): clay mineralogy, grain size, formatting pressure, and water content. Five soils with different mineralogical composition were used to study the first parameter. 12.5, 25, 40 and 60% of aggregates sized 0/2, 0/4 and 0/6.3 mm were added to the soil to study the second parameter. CEB were compacted at 100, 200 and 300 kN to study the third parameter. 3, 6 and 10% of water were used to study the fourth parameter. Test specimens were produced using a hydraulic press and characterized by compression. The characterization of the specimens shows that the compressive strength increases with the smectite content. Compressive strength does not always increase with changing particle size. Compressive strength increases with increasing formatting pressure, while increasing water content decreases compressive strength. This study also shows that the compressive strength of CEB is improved differently for each soil type.

1. Introduction

Raw earth has been used as a building material for eleven millennia on all continents. This makes it one of the oldest building materials in human history. According to UNESCO, 135 sites (20% of the total number) recorded as World heritage are entirely or partially built on raw earth [1]. Over time, raw earth has emerged as one of the building materials favored by man. The Syrian city of Tell Feres, over 7000 years, old and the Citadel of Ulug Dépé, over 5000 years, old in Turkmenistan are some examples. In Antiquity and the Middle Ages, several earthen constructions were made, such as the ancient city of Volubis in Morocco, or the great Kyz Kala in Merv in Turkmenistan. In many rural areas of Latin America, Asia, and Africa, raw earth has been and is being used as a preferred building material [1, 2, 3].

Due to current environmental concerns related to climate change, resource depletion, global housing needs [4, 5, 6, 7], raw earth is being honored. There are many earth building techniques. Wattle and daub is a technique in which the earth is used by filling a wooden structure. Rammed earth is a wall construction that consists of compacting the earth in a formwork. Adobe is a masonry in blocks made manually in wooden molds. Cob is a technique made by handmade earth balls consisting of mixing the earth and plant fibers. In the 1950s, Compressed Earth block (CEB) masonry appeared, consisting of compacting the earth with a manual or mechanical press [8]. This technique is the subject of this study.

The objective of this work is to study parameters affecting the compressive strength of materials in CEB. To meet this objective, the manufacture of CEB was made on 5 different soils.

The compressive strength of CEB influences its resistance to deterioration over time, i.e., resistance to water action, abrasion resistance, freeze-thaw resistance, or resistance to mechanical stress [9, 10, 11, 12, 13, 14]. The higher the value of the compressive strength is, the higher the lifetime of the CEB will be [15, 16].

Several parameters influence the compressive strength of CEB: the bulk density [17], the soil composition [18, 19], the nature of the stabilizer used [18], the degree of compaction [19], [20], the age of CEB [18], the surface texture [19] etc. In this work, four parameters that can affect the compressive strength of CEB are studied: the nature of clay minerals present in the soil sample, the particle size, the formatting pressure, and the quantity of added water. Five soils that differ in their mineralogical composition have been used to study the effect of the nature of clay minerals on the compressive strength of CEB. Aggregates of 0/2, 0/4, and 0/6.3 mm were added in four proportions 12.5, 25, 40, and 60% to 5 soils to study the effects of particle size on compressive strength. The effect of the formatting pressure on the compressive strength of CEB was made by compacting 5 soils at 3 distinct formatting pressures: 100, 200, and 300 kN. The effect of added water on the compressive strength of CEB was made by adding 3, 6, and 10% of water to 5 soils.

2. Materials and methods

Test pieces were produced using a LPP 150-500/100 Max Voggenreiter mavo hydraulic press. The sample were placed into the press mold and compressed with a piston. The formatting pressure varied between 100 and 300 kN. Cubic test pieces measuring 7x7x7 cm^3 (length x width x height) are obtained. Test pieces were made in the Belgian Ceramic Research Center laboratory (BCRC) in Mons.

The compressive strength of the cubic test pieces was made in the BCRC laboratory using a TONIUNIVERSAL device (Figure 1) according to standard XP P13-901 [21].

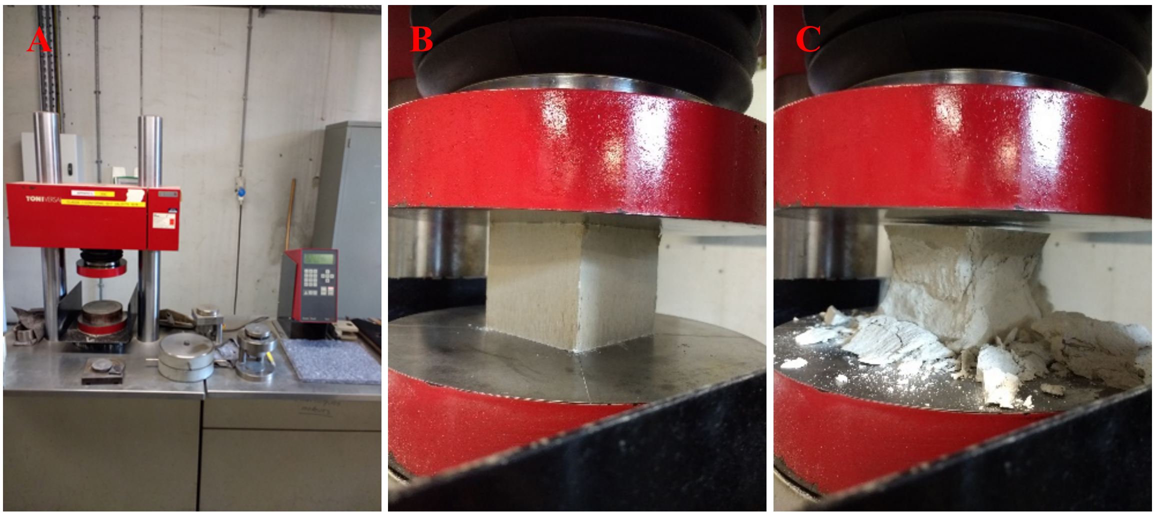

Figure 1. Compression test device (A); sample compression (B); rupture of the sample (C).

The characterization of soil samples was based on mineralogical studies (total mineralogy and clay mineralogy by X-ray diffraction) and geotechnical analyzes (organic matter, methylene blue, Atterberg limits, granulometry and drying shrinkage). This was carried out in Argiles, Géochimie et Environnement sédimentaires laboratory, University of Liège. Samples for X-ray diffraction were prepared according to the protocol proposed by Moore and Reynolds [22]. EVA software was used to read the diffractograms of X-ray diffraction to identify the mineral phases. Organic matter content, methylene blue, Atterberg limits, particle size and drying shrinkage tests were carried out according to standards NF P94-055 [23], NF P94-068 [24], NF P94-051 [25], NF P94-056 [26] and NZS 4298 [27]. Table 1 summarizes the properties of the soils used. According to the USCS [28], A and E soils can be classified as inorganic clayey silts, while B, C and D soils as inorganic silty clays with low plasticity.

Table 1. Properties of the 5 soils selected.

Properties	**A**	**B**	**C**	**D**	**E**
Organic matter (%)	3.0	8.9	4.7	6.4	2.0
Atterberg limits					
Liquidity LL	25.	33.	27.	30.	30.
Plasticity PL	3	9	2	7	0
Plasticity index *PI*	21.	28.	19.	24.	27.
	5	8	2	5	1
	3.8	5.1	8.0	6.2	2.9
Drying shrinkage (%)	4.7	13.	6.7	12.	2.8
		2		3	
Methylene blue value (gr)	2	6	4	6	1
Laser granulometry (%)					
< 2 µm	23	52	26	32	37
< 63 µm	61	98	47	91	73
< 125 µm	65	100	54	100	89
< 250 µm	67		86		100
< 500 µm	69		100		
< 1 mm	75				
< 2 mm	88				
< 4 mm	100				
Mineralogy (%)					
Quartz	46	59	60	60	39
Plagioclase	8	5	4	8	8
Orthoclase	6	10	7	10	5
Calcite	/	/	/	/	5
Dolomite	/	1	/	/	4
Clay minerals	40	26	29	22	39
Illite	*86*	*14*	39	*40*	*76*
Chlorite	/	/	/	*17*	/
Kaolinite	*14*	*39*	9	*2*	*24*
Smectite	/	*48*	43	*41*	/

3. Results and discussion

3.1. Influence of the nature of clay minerals and particle size on compressive strength

Test pieces were produced with a formatting pressure of 300 kN. A soil volume was dosed to be mixed with granulate. 6 % of water was added. Three granulometries of sandstone granulate were used, 0/2, 0/4, and 0/6.3 mm. The grain size curves of these three granulometries are presented in Figure 2. For each aggregate granulometry, the manufacture of test pieces was carried out according to four formulations: with 12.5, 25, 40 and 60% of aggregates in volume. After mixing, 3 test pieces were made for each mixture. After demolding, test pieces were weighed and measured before being dried in open air at 21° ± 2°C for 1 week until completely dry. Complete drying has been achieved when the mass measured between two successive days did not change. Then, the values of the density and compressive strength of the test pieces were measured. Tables 2 and 3 give the results of the bulk density and compressive strength values.

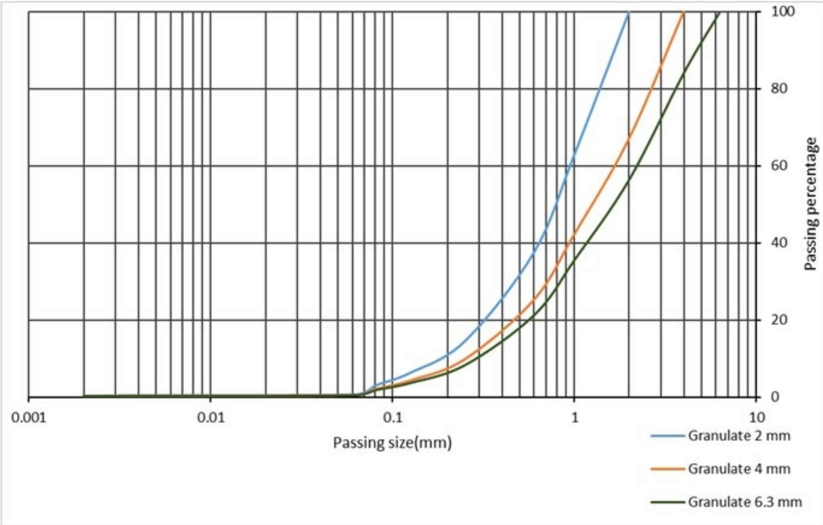

Figure 2. Granulometric curves of the aggregates used.

Table 2. Average dry bulk densities.

Samples	**% added aggregate**	**Bulk densities (gr/cm³)**		
		Aggregate 2 mm	Aggregate 4 mm	Aggregate 6.3 mm
A	0		2.11	
	12.5	2.25	2.20	2.23
	25	2.27	2.24	2.29
	40	2.31	2.28	2.35
	60	2.35	2.30	2.36
B	0		2.08	
	12.5	2.19	2.23	2.24
	25	2.20	2.24	2.25
	40	2.22	2.26	2.27
	60	2.25	2.30	2.30
C	0		2.14	
	12.5	2.31	2.23	2.26
	25	2.31	2.30	2.31
	40	2.31	2.31	2.32
	60	2.32	2.31	2.34
D	0		2.09	
	12.5	2.22	2.22	2.22
	25	2.24	2.26	2.26
	40	2.28	2.26	2.27
	60	2.29	2.30	2.30
E	0		2.01	
	12.5	2.05	2.06	2.07
	25	2.10	2.12	2.25
	40	2.18	2.20	2.33
	60	2.22	2.29	2.38

Table 3. Average compressive strengths.

Sample	% added aggregate	Compressive strength (MPa)		
		Aggregate 2 mm	Aggregate 4 mm	Aggregate 6.3 mm
A	0		2.83	
	12.5	2.1	2.82	2.81
	25	2.23	2.95	3.21
	40	2.25	2.98	3.36
	60	2.74	3.69	3.55
B	0		11.71	
	12.5	14.91	14.79	14.19
	25	13.04	12.7	10.51
	40	11.44	10.56	10.36
	60	10.22	9.53	9.54
C	0		9.69	
	12.5	11.69	11.29	11.09
	25	10.17	9.66	9.40
	40	8.69	7.78	7.68
	60	7.57	6.42	6.17
D	0		8.95	
	12.5	12.53	12.41	11.97
	25	11.39	11.31	10.76
	40	9.88	9.66	8.24
	60	8.23	8.84	7.72
E	0		1.91	
	12.5	1.72	2.29	2.5
	25	2.23	2.4	2.47
	40	2.04	2.58	2.61
	60	3.25	3.22	3.45

3.1.1. Nature of clay minerals. A and E samples have a lower compressive strength than the other three samples. For samples B, C, and D, the compressive strength increases with increasing clay content (Table 2). Sarsby [29] shows that plastic clays give better compactness, and thus, better compressive strength. The best results of compressive strength are obtained with sample B, which is more plastic (Table 3). The non-plastic nature (plasticity index <5) of A and E samples results in a low resistance to compression. A and E samples contain only kaolinite and illite which results in their low plasticity, while samples B, C, and D also contain smectite which increases their plasticity (Table 1). Table 2 shows that the dry bulk density decreases with the liquidity limit increasing (LL) as plastic clays are more compactable [30]. LL B > LL D > LL C (Table 2), hence the dry bulk density C > D > B.

3.1.2. Particle size. The bulk density (Table 2) increases with the addition of aggregates for all samples. By increasing the percentage and the size of aggregates, the mass of the sample is increased more significantly than its volume. In other words, the bulk density decreases with the percentage of clay content. Sample E reaches a compressive strength of 1.91 MPa without the addition of aggregate, and reaches a maximum value of 3.45 MPa with 60% of the aggregate 6.3 mm (Table 3). The addition of granulate improves the compressive strength of this sample. The best result is obtained with the 6.3 mm granulate. Sample A reaches a compressive strength of 2.83 MPa without addition of aggregates, and reaches a maximum value of 3.69 MPa with 60% of aggregate with a diameter of 4 mm. The addition of 2 mm granulate does not improve its compressive strength. The best result is obtained with the aggregate 4 mm. Aggregates act in the case of E and A samples as a stabilizer preventing the development of decompression cracks. By releasing the pressing pressure, microcracks appear on the test piece, which weaken it. Samples B, C, and D show an increase of compressive strength with the increase of the percentage of aggregate compared to the sample without aggregates (Table 3). Samples B, C and D show a decrease in compressive strength with increasing aggregate percentage from 12.5 to 60% and aggregate diameter from 2 to 6.3 mm. The best results for these 3 soils are obtained with the 2 mm aggregate. Ben Ayed et al. [31] show that the compressive strength increases with clay content, due to the infiltration of clay into the matrix pores forming rigid connections binding coarser grains. Proctor [32] demonstrated that compaction depends on particle size. By increasing the aggregates size, the spread of the granulometric curve is increased, preventing the fine particles to fill all voids. Thus, the compressive strength of the material decreases [32, 33]. In other words, when the percentage of large particles increases in the mixtures, the samples have more voids. This explains the decrease of the compressive strength of B, C, and D samples with the increase of the aggregates size.

3.2. Influence of the formatting pressure on the compressive strength of CEB

The compressive strengths of the test pieces were measured at different formatting pressures (compressive forces). Five soils without granulates were used. They were mixed with 3% of water and then compressed to 100, 200, and 300 kN. Three test pieces were made for each measurement. The average values of compressive strength and bulk density are presented in Table 4.

Table 4. Average compressive strength and bulk density of test pieces.

Samples	Average compressive strength (MPa)			Average bulk densities (gr/cm^3)		
Forming pressure	100 kN	200 kN	300 kN	100 kN	200 kN	300 kN
A	1.54	2.54	3.28	1.99	2.03	2.11
B	10.62	13.86	18.61	1.96	2.09	2.17
C	9.94	11.27	14.89	2.07	2.18	2.27
D	10.90	14.59	18.06	1.98	2.09	2.14
E	0.82	0.91	1.47	1.86	1.94	1.98

Compaction allows to densify the soil by reducing the air volume [34]. Increasing the formatting pressure from 100 to 300 kN increases the bulk density and compressive strength of all samples (Table 4). Attom [35] shows that increasing the compaction energy reduces the optimal water content and increases the bulk density. Increasing the bulk density increases the contact points between grains by decreasing the porosity and allows to increase the compressive strength (table 4).

3.3. Influence of the amount of water added on the compressive strength of CEB

The influence of water amount on the compressive strength was evaluated starting from 3% to 10% of water, for two formatting pressures, i.e., 100 and 200 kN. The average values of the compressive strengths are shown in Table 5. The average values of the bulk density are presented in Table 6.

Soil contains solid particles, water, and air. Air allows water movements in the soil. If there is too much water, compaction is not possible. However, if there is little water, the friction between particles is too great and the compaction is inadequate [30]. Drnevich [36] shows that when the water content is low, the soil is rigid and difficult to be compressed. The bulk density remains low because the air content remains high. When the water content increases, water acts by lubricating the particles and allowing them to be arranged as densely as possible. This decreases the air content and densifies the material. When the water content is further increased, water and air tend to keep the soil particles separate, and to prevent the decrease of air content and consolidation, because a significant portion of the compaction energy is absorbed by the incompressible water and is therefore not communicated to the soil grains. The total voids increase with the water content and thus the dry bulk density of the soil decreases. Bulk density decreases with increasing water content for all soils regardless of the compaction energy (Table 6). This results in a decrease in the compressive strength (Table 5). Camapum De Carvalho et al. [37] show that soils with high plasticity are not very sensitive to the modification of water content by compaction. The decrease in compressive strength with the increase in water content C > D and B soils, because PL B > PL D > PL C (Table 1).

Table 5. Average compressive strength (MPa) and water content with formatting pressure of 100 kN and 200 kN.

Samples	**Average compressive strength (MPa) forming pressure 100 kN**			**Average compressive strength (MPa). forming pressure 200 kN**		
Water content %	3 %	6 %	10 %	3 %	6 %	10 %
A	2.64	2.62	1.85	2.84	2.54	2.35
B	10.62	10.53	8.17	13.86	12.24	8.38
C	9.94	9.04	5.10	11.27	8.87	4.45
D	10.90	10.31	8.00	14.59	11.08	6.39
E	0.82	0.71	0.59	0.91	0.91	0.89

Table 6. Average bulk density (gr/cm^3) and water content with formatting pressure of 100 kN and 200 kN.

Samples	**Average bulk densities (gr/cm^3) – Forming pressure = 100 kN**			**Average bulk densities (gr/cm^3) – Forming pressure = 200 kN**		
% water	3 %	6 %	10 %	3 %	6 %	10 %
A	2.06	2.05	2.05	2.05	2.03	2.03
B	2.0	1.96	1.93	2.09	2.06	1.93
C	2.07	1.99	1.96	2.18	2.10	1.94
D	2.04	1.98	1.88	2.09	2.05	1.93
E	1.89	1.86	1.86	1.95	1.94	1.94

4. Conclusions

Four parameters influencing the compressive strength of Compressed Earth Blocks were studied.

- Nature of clay minerals: five soil samples A, B, C, D, and E were used. The characterization of test pieces produced on these 5 soils showed that resistance to compression may increase with the soil plasticity and smectite content.
- Particle size: test pieces were produced by varying the size of the aggregates. Three particle sizes were used: 0/2, 0/4, and 0/6.3 mm. The best results of compressive strength are obtained with 6.3 mm granulate for E soil, 4 mm for A soil, and 2 mm for B, C, and D samples. The aggregates 0/2, 0/4, and 0/6.3 mm were added in proportions of 12.5, 25, 40, and 60%. The addition of 0 to 60% granulate improves the compressive strength of soils A and E. The samples B, C, and D show a decrease in the compressive strength with the increase of the percentage of granulate from 12.5 to 60%. Varying the particle size of a soil has a different influence on the compressive strength of each type of soil
- Compressive strengths were measured on test pieces compressed with three formatting pressures: 100, 200, and 300 kN. Compressive strength increases with increasing formatting pressure. The increase of formatting pressure allows to increase the compressive strength.
- : The influence of the quantity of added water on the compressive strength was evaluated by adding 3, 6, and 10% of water. The resistance to compression decreases with increasing water content.

For each type of soil, it is possible to increase the compressive strength of the CEB by acting on the nature of clay minerals, the particle size, the formatting pressure, and the quantity of added water. Five soils were chosen to answer to the question of how to improve CEB compressive strength. Expanding this study to other soils and other characteristics such as freeze-thaw resistance and resistance to water is a perspective of this work.

References

[1] Anger R, Fontaine L, Joffroy T and Ruiz E 2011 Construire en terre, une autre voie pour loger la planète *Secteur Privé & Développement, revue bimestrielle de Proparco* ⟨hal-00953709⟩
[2] Doat P, Hays A, Houben H and Matuk S 1979 *Construire en terre* (Paris: Alternatives et Parallèles)
[3] Anger R and Fontaine L 2009 *Bâtir en terre, du grain de sable à l'architecture* (Paris: Belin)
[4] United Nations Environment Programme 2016 *Global environment outlook: GEO-6: assessment for the Pan-European region* (Nairobi: United Nations Environment Program)
[5] Magniont C 2000 *Contribution à la formulation et à la caractérisation d'un écomatériau de construction à base d'agroressources* (Université de Toulouse : Toulouse)
[6] Niroumand H, Barcelo J A, Kibert C J and Saaly M 2017 Evaluation of Earth Building Tools in Construction (EBTC) in earth architecture and earth buildings *Renew. Sust. Energ. Rev.* **70** 861-866
[7] Morel J C, Pkla A and Walker P Compressive strength testing of compressed earth blocks *Constr. Build. Mater.* **21** (2) 303-309
[8] Houben H and Guillaud H 1995 *Traité de construction en terre* (Marseille: Parenthèses)
[9] Ogunye F O and Boussabaine H 2002 Diagnosis of assessment methods for weatherability of stabilised compressed soil blocks *Constr. Build. Mater.* **16** 163-172
[10] Standards New Zealand 1998 *Materials and workmanship for earth buildings* (Wellington: New Zealand)
[11] Bui T T, Bui Q B, Limam A and Maximilien S 2014 Failure of rammed earth walls: from observations to quantifications *Constr. Build. Mater.* **51** 295–302
[12] Ogunye F O and Boussabaine H 2002 Development of a rainfall test rig as an aid in soil block weathering assessment *Constr. Build. Mater.* **16** 173-180
[13] Hall M R 2005 Assessing the environmental performance of stabilised rammed earth walls using a climatic simulation chamber *Build. Environ.* **42** 139-145
[14] Guerin L 1985 *Construction à faible cout dans les programmes spéciaux de travaux publics: Principes directeurs pour l'emploi de la terre crue* (Genève: Bureau international du travail)
[15] Heathcote K A 1995 Compressive strength of earthwall buildings *Constr. Build. Mater.*, **9** (3) 185-189
[16] Guettala A, Abibsi A and Houari H 2006 Compressive strength study of stabilized earth concrete under both laboratory and climatic conditions exposure *Constr. Build. Mater.* **20** 119-127
[17] Patty R L 1936 The Relation of Colloids in Soil to its Favorable use in Pise or Rammed Earth Walls, South Dakota *Agricultural Experiment Station* **298**
[18] Heathcote K A 2002 *An investigation into the erodibility of earth wall units* (Sydney: University of Technology)
[19] Crowley M 1997 Quality Control for Earth Structures *Australian Institute of Building Papers* **8** 109-119.
[20] Moevus M, Fontaine L and Anger R 2012 *Caractéristiques mécaniques, thermiques et hygrométriques du matériau terre crue : bilan de la littérature* ed CRATerre-EAG (Grenoble: Ministère de l'Écologie, du Développement durable, des Transports et du Logement)
[21] AFNOR 2001 *XP P13-901 - Blocs de terre comprimée pour murs et cloisons : définitions – Spécifications – Méthodes d'essais – Conditions de réception* (La Plaine Saint-Denis:

Editions AFNOR).
[22] Moore D M and Reynolds R C 1989 *X-ray Diffraction and the Identification and Analysis of Clay Minerals* (Oxford: Oxford University Press)
[23] AFNOR 1993 *NF P94-055 Sols : reconnaissance et essais - Détermination de la teneur pondérale en matières organiques d'un sol - Méthode chimique* (La Plaine Saint-Denis: Editions AFNOR)
[24] AFNOR 1998 *NF P94-068 Sols : reconnaissance et essais - Mesure de la capacité d'adsorption de bleu de méthylène d'un sol ou d'un matériau rocheux - Détermination de la valeur de bleu de méthylène d'un sol ou d'un matériau rocheux par l'essai à la tache* (La Plaine Saint-Denis: Editions AFNOR)
[25] AFNOR 1993 *NF P94-051 Sols : reconnaissance et essais - Détermination des limites d'Atterberg - Limite de liquidité à la coupelle - Limite de plasticité au rouleau* (La Plaine Saint-Denis: Editions AFNOR)
[26] AFNOR 1996 NF P94-056 Sols : reconnaissance et essais - Analyse granulométrique - Méthode par tamisage à sec après lavage (La Plaine Saint-Denis: Editions AFNOR)
[27] NZS 4298 2015 *Materials and workmanship for earth buildings* (Wellington: Standards New Zealand)
[28] ASTM Committee D-18 on Soil and Rock 2011 *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)* (Philadelphia, Pa: ASTM International)
[29] Sarsby R W 2013 *Environmental Geotechnics* second edition (London, Ice Publishing).
[30] Zhong-Sen L 2015 *Études des propriétés hydromécaniques des sols argileux non saturés proches de la saturation* (Paris: École centrale des arts et manufactures, école centrale)
[31] Ben Ayed H, Limam O and Kallel A 2011 Béton d'argile : application aux briques de terre comprimée *INVACO2 Séminaire International, innovation & valorisation en génie civil & matériaux de construction*
[32] Proctor R R 1933 Fundamental Principles of Soil Compaction *Engineering News-Record* **111** 9-13.
[33] Taghiloha L 2013 *Using rammed earth mixed with recycled aggregate as a construction material* (Barcelona: Ecola de Camins)
[34] Craig R F 1987 *Craig's Soil Mechanics* (Dundee: Spon Press)
[35] Attom M F 1997 The effect of compactive energy level on some soil properties *Applied Clay Science* **12** (1-2) 61–72,
[36] Drnevich V E 2007 *A Study of Effective Soil Compaction Control of Granular Soils* (West Lafayette: Purdue University)
[37] Camapum De Carvalho J, Crispel J J, Mieussens C and Nardone A 1987 *La reconstitution des éprouvettes en laboratoire, théorie et pratique, Rapport de recherche LPC n°145* (Paris: Ministère de l'équipement, du logement, de l'aménagement du territoire et des transports)